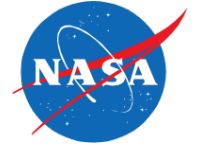


A Plan for Revolutionary Change in Gas Turbine Engine Control System Architecture

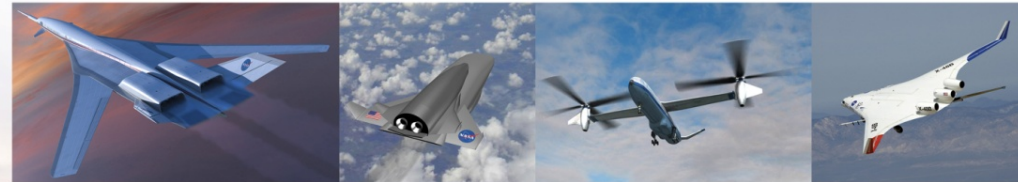
**Dennis Culley
Controls and Dynamics Branch
NASA Glenn Research Center**

The implementation of Distributed Engine Control technology on the gas turbine engine has been a vexing challenge for the controls community. A successful implementation requires the resolution of multiple technical issues in areas such as network communications, power distribution, and system integration, but especially in the area of high temperature electronics. Impeding the achievement has been the lack of a clearly articulated message about the importance of the distributed control technology to future turbine engine system goals and objectives. To resolve these issues and bring the technology to fruition has, and will continue to require, a broad coalition of resources from government, industry, and academia. This presentation will describe the broad challenges facing the next generation of advanced control systems and the plan which is being put into action to successfully implement the technology on the next generation of gas turbine engine systems.



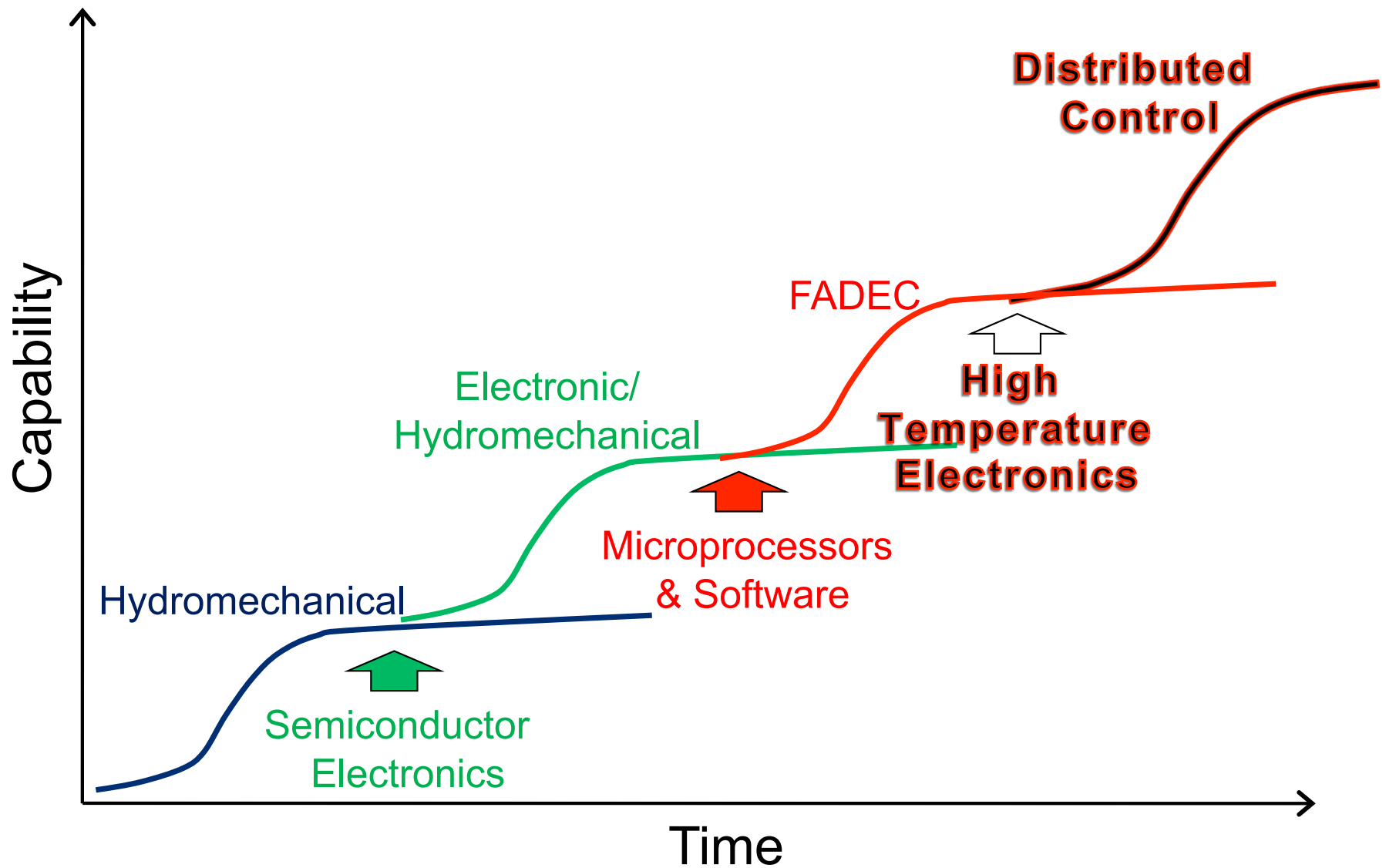
A Plan for Revolutionary Change in Gas Turbine Engine Control System Architecture

Dennis Culley
Research Engineer
Glenn Research Center, Controls & Dynamics Branch



The Ohio State University
April 18, 2011
Columbus, Ohio

Gas Turbine Engine Control Technology





Why Do We Want/Need Distributed Engine Control?

- System Drivers and Constraints
- Stakeholder Perspectives

What Do We Expect From Distributed Control?

- Objectives for New Technology Development

What is Preventing Us from Getting There?

- Technical Challenges for Distributed Control

What is the Go Forward Plan?

- Vision
- Development Plan

Summary and Conclusions



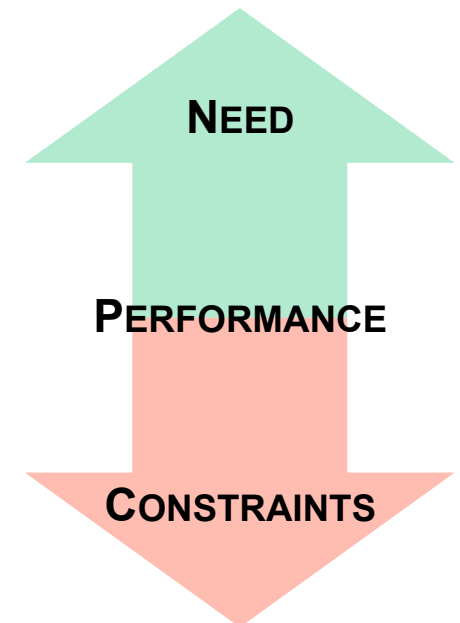
Why Do We Want/Need Distributed Engine Control?

System Drivers and Constraints



Performance drivers and constraints which are compelling the next revolutionary step in engine control

- The need for improved performance drives a need for more control, implying more processing capability, additional volume, weight, and heat dissipation.
- The reality of more efficient engines (smaller core) results in less available mounting envelope for controls and a hotter environment with less capacity to reject heat.

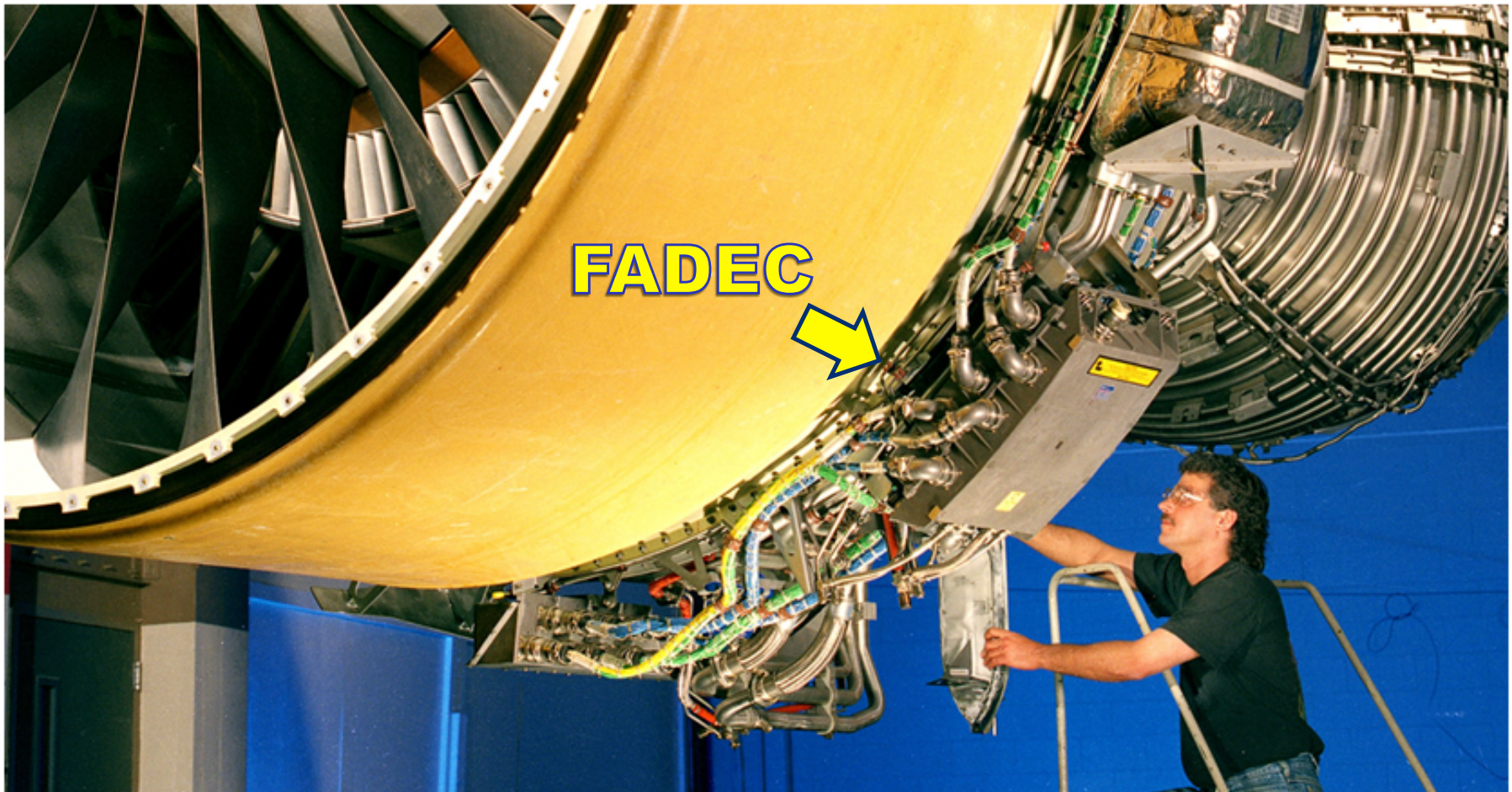


Control systems typically account for 15 - 30% of engine system weight & cost and are the pacing item in engine system development

Commercial Control Implementation



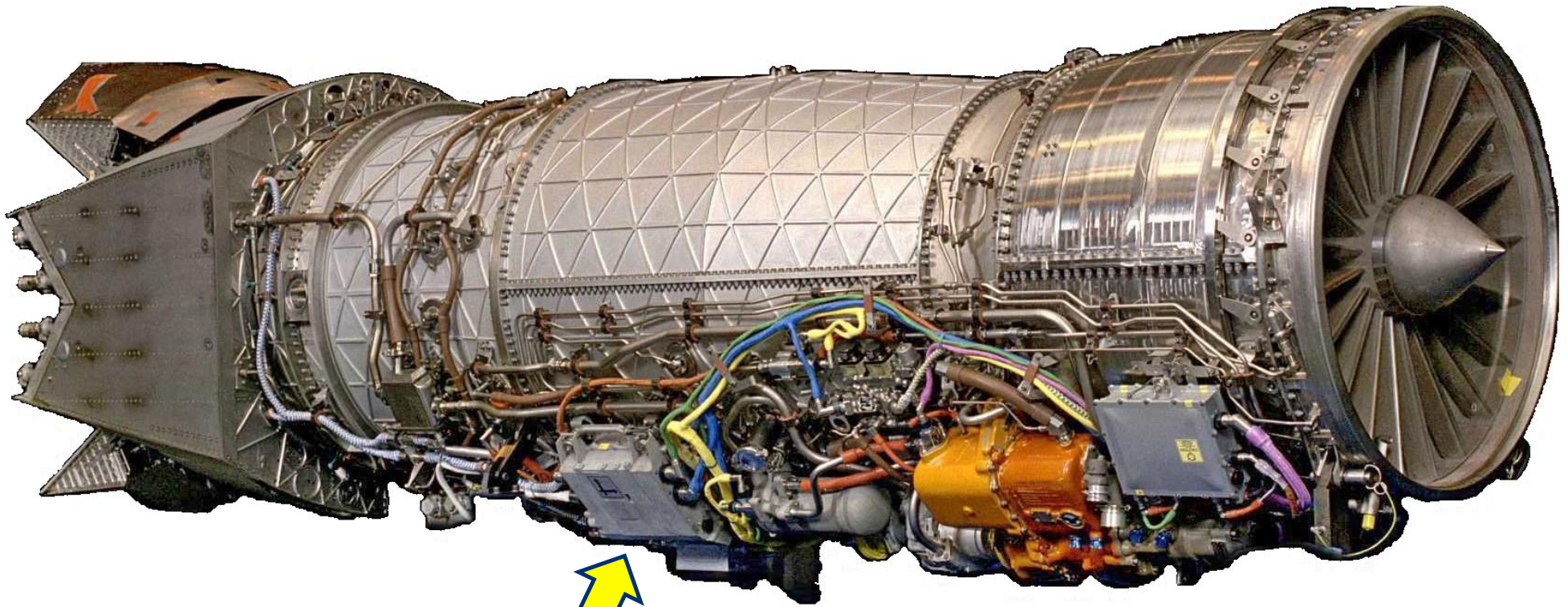
Fan Case Mounted - Air Cooled



Military Control Implementation



Core Mounted - Fuel Cooled



FADEC

System Drivers and Constraints



Affordability considerations

- There is a cost for developing new technology
- There is a cost for not investing in new technology in terms of lost opportunities for improved performance



Development of new technology does not guarantee adoption on production systems because customers are reluctant to buy more capability than they presently need

Customers don't buy technology, they buy capability

Stakeholder Perspectives



Progress in control system capability is predicated on advances in **commercial** microprocessor technology

- There is virtually no viable alternative to the dependence on engine control capability and the high performance microprocessor

There is virtually **no influence** on the commercial electronics market from the turbine engine controls community

- Electronics obsolescence is a primary factor in control system cost

Most control resources (money, manpower, time) are used to satisfy **non-recurring engineering** (NRE) issues related to the design, unplanned redesign, and upgrades to engine control systems

- There is very little re-use of control hardware due to requirement flow down and regulations governing the qualification of systems

A capability for Distributed Engine Control Architecture can have a major impact on the engine system performance and cost structure but the business case has not been made

NASA Subsonic Transport System Level Metrics

.... technology for dramatically improving noise, emissions, & performance



CORNERS OF THE TRADE SPACE	N+1 (2015) ^{***} Technology Benefits Relative to a Single Aisle Reference Configuration	N+2 (2020) ^{***} Technology Benefits Relative to a Large Twin Aisle Reference Configuration	N+3 (2025) ^{***} Technology Benefits
Noise (cum below Stage 4)			
LT ONOx Emissions (below CAEP 6)	-60%		
Performance: Aircraft Fuel Burn			
Performance: Field Length	-33%		

^{***} Technology Readiness Level for Key technologies =46

^{**} Additional gains may be possible through operational improvements

^{*} Concepts that enable optimal use of runways at multiple airports within the metropolitan areas

SFW Approach

- Conduct Discipline-based Foundational Research
- Investigate Advanced Multi-Discipline Based Concepts and Technologies
- Reduce Uncertainty in Multi-Disciplinary Design and Analysis Tools and Processes
- Enable Major Changes in Engine Cycle/Airframe Configurations



What Do We Expect from Distributed Engine Control?

Propulsion Controls – SFW Objectives



Provide Critical Path Technology for Extremely Efficient Engines (UHB):

- *Combustion Control* - lower emissions
- *Flow Control* - improved aerothermodynamic efficiency, fuel burn
- *Stability Control* - lower weight, field length

Achieve Additional Control System Enhancements Supporting SFW Goals:

- Directly reduce engine weight (e.g., reduce harness weight)
- Improve propulsion responsiveness (e.g., local control loop closure)
- Increase system performance (e.g., adaptive / intelligent control)

Complement ARMD Objectives:

- Improved vehicle performance by enabling highly integrated propulsion/airframe control – e.g., asymmetric thrust balancing

***Enabled by
Transition to Modular, Distributed, and Embedded Functionality***

Objectives for New Technology Development



Retain access to the use of commercial microprocessor technologies to implement the complex control laws and the new engine technologies which will enable future engine system performance improvements.

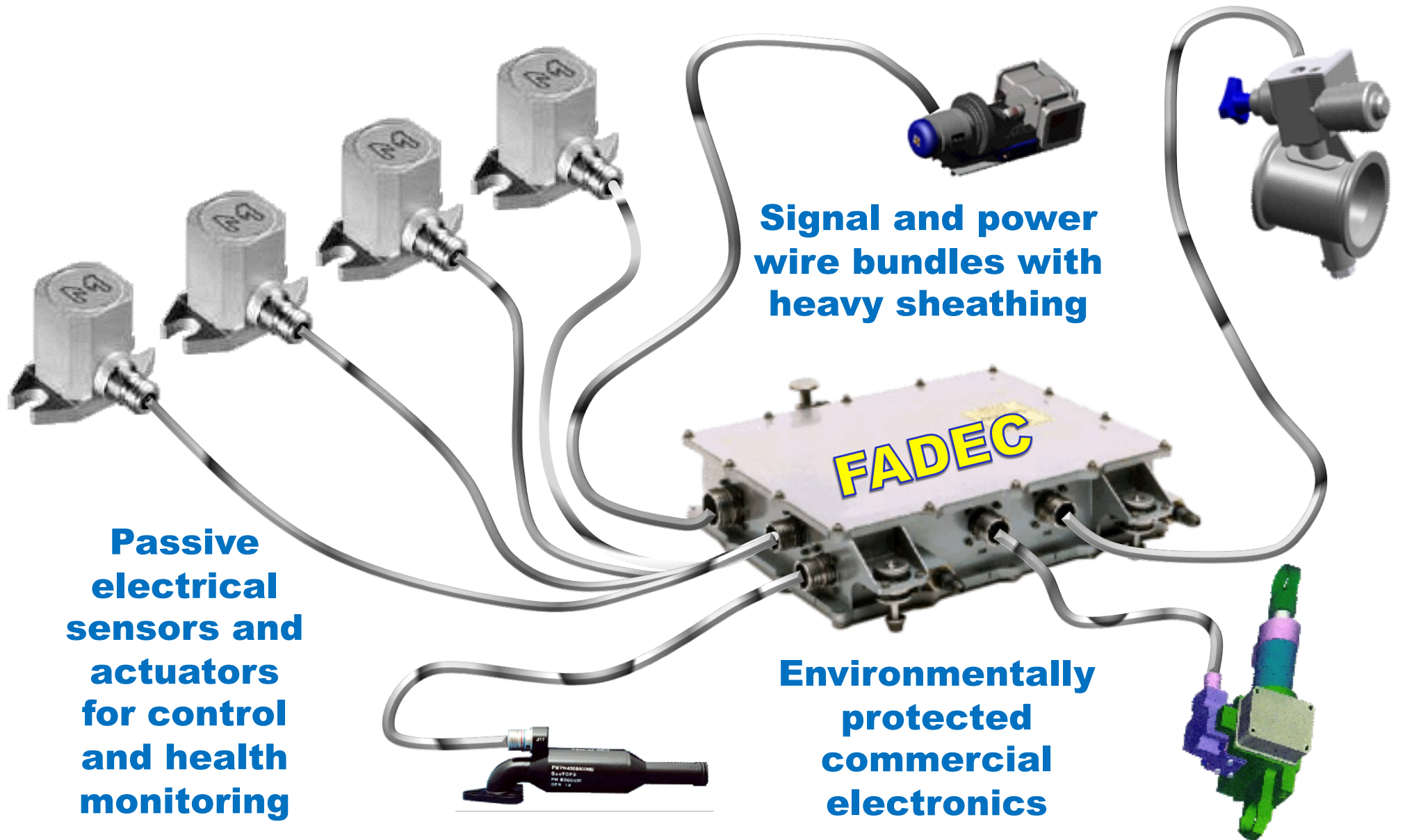
Address the disruptive issue of electronic component obsolescence.

Develop system level technologies which enable reduction of NRE

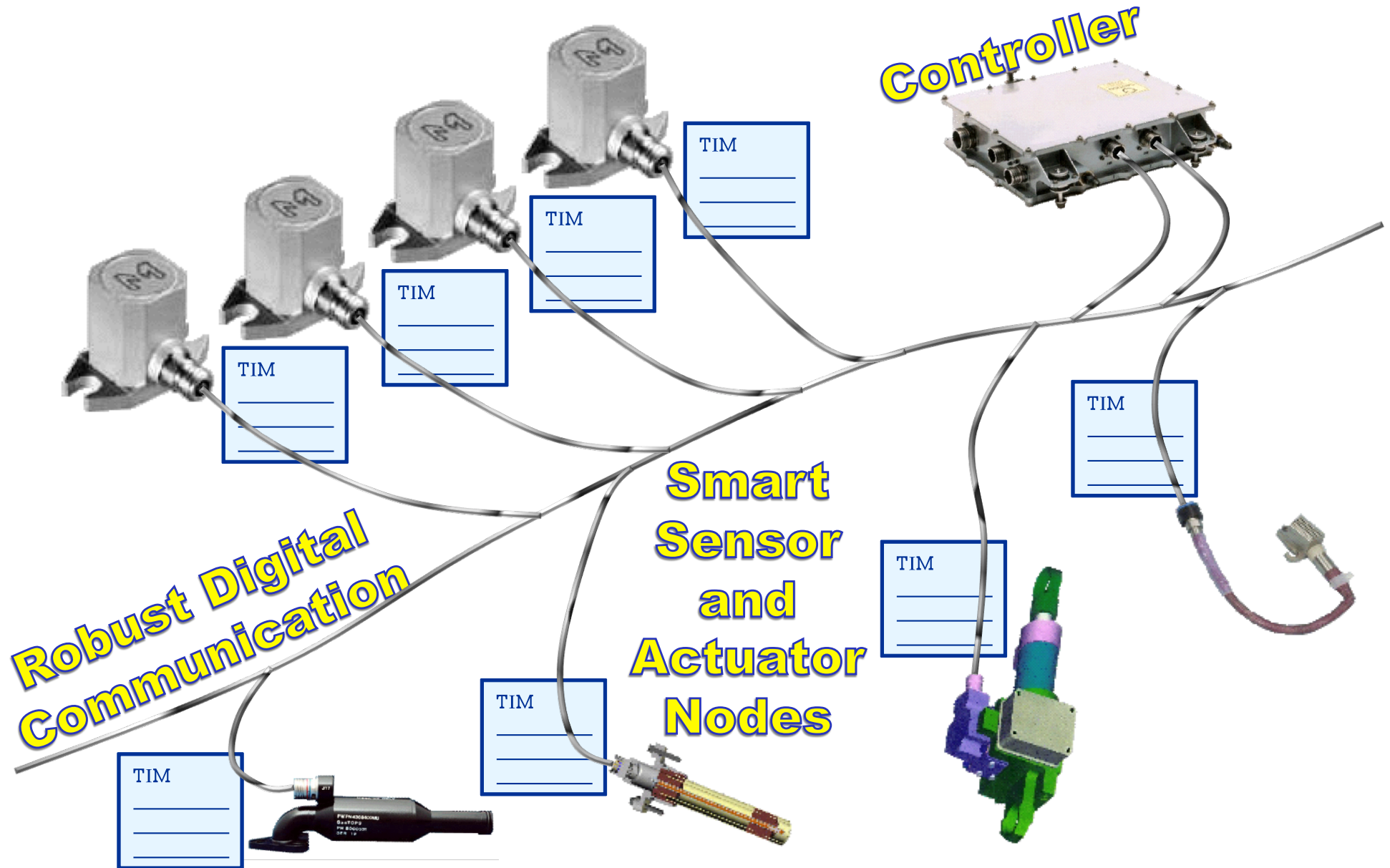
- To increase application of resources to value-added technologies
- To increase the insertion of new technology by decreasing development costs
- To decrease life-cycle costs by enabling reuse of components across platforms and from multiple suppliers

The engine control system should never be the limiting factor in engine system performance

Centralized Control Architecture



Distributed Control Architecture





What is Preventing Us from Getting There?

Technical Challenges for Distributed Control



Networked Communications

- Enables the separation of control law processing from I/O
- Over time will require much higher bandwidth primarily for diagnostics

Power Distribution

- I/O is the primary driver for unique power requirements
- Lower weight will result with the distribution of common power and unique power developed in the end-element

High Temperature Electronics

- The fundamental technology which enables modularity of distributed components in the engine environment without incurring a weight penalty
- Initial focus is on cost reduction with a long term strategy for improved functional capability

Systems Integration

- Optimal life-cycle cost reduction for the full engine system can only be realized with improved processes for the design, integration, and verification of modular components and systems

Technical Challenges for Distributed Control



High Temperature Electronics

Centralized: Commercially available electronics, limited to 125 C junction temperature, in a controlled environment.

Distributed: Need to survive as embedded components on the engine without active cooling.

- Are all the electronics technologies developed? If not, how will they be developed?
- What are the requirements?
- What will be the cost?
- Is there more than one source? Are they reliable? Are they available for the long term?
- What is the growth path?

Technical Challenges for Distributed Control



Networked Communications

Centralized: “Communication” is typically controlled by hardware in the FADEC.

Distributed: Communications is a widely dispersed function outside of the FADEC.

- What are the failure modes?
- How does it affect engine stability?
- Is there a common communication protocol that can be developed across industry?
- What are the requirements?
- How is it constrained by the high temperature electronics?
- How will it evolve over time?

Technical Challenges for Distributed Control



Power Distribution

Centralized: Power distribution is system specific and housed inside the FADEC.

Distributed: Power requirements cannot be precisely known

- Is there a common power specification that can be developed across industry?
- What is the envelope of requirements for future I/O?
- How does distribution affect engine weight?
- What are the thermal considerations?
- How is reliability impacted?

Technical Challenges for Distributed Control



Systems Integration

Centralized: System is uniquely designed and certified.

Distributed: Components must be individually certified.

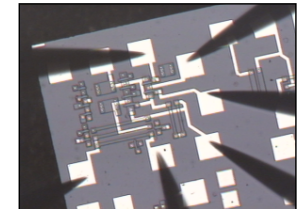
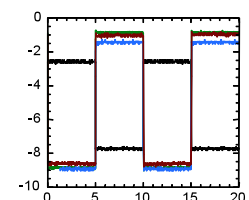
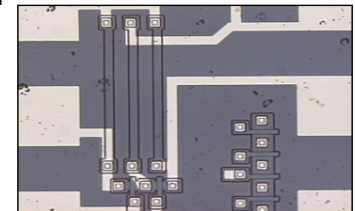
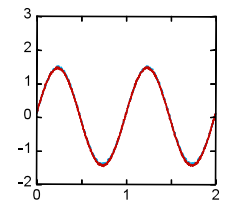
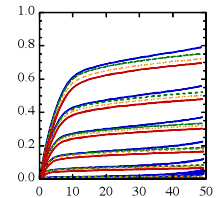
- What regulatory issues must be addressed/modified?
- How will compliance be measured?
- What tools need to be developed?

Technical Progress

in Silicon Carbide (SiC) High Temperature Electronics



- Demonstrated durability of discrete SiC JFET transistors.
 - World record 10,000 hours operation at 500 °C with excellent stability and operational characteristics
 - **Fundamental Building Block of All Analog and Digital Circuits**
- Demonstrated capability for SiC integrated circuits. Interconnect structures are CRITICAL technology for high density packaging.
 - SiC JFET Analog Differential Amplifier, world record 5,000 hours operation at 500 °C
 - **Fundamental Circuit for all Analog Functions**
 - SiC JFET Digital NOR Gate, world record 3,000 hours operation at 500 °C
 - **Fundamental Circuit for all Processor and Logic Functions**
- Multi-level interconnect structure milestone expected this year
 - Capability for 1000 transistors on a common substrate at 500 °C
 - **Fundamental requirement for embedded smart devices**



Progress is directed at development of embedded smart sensors, actuators, and subsystem control capabilities

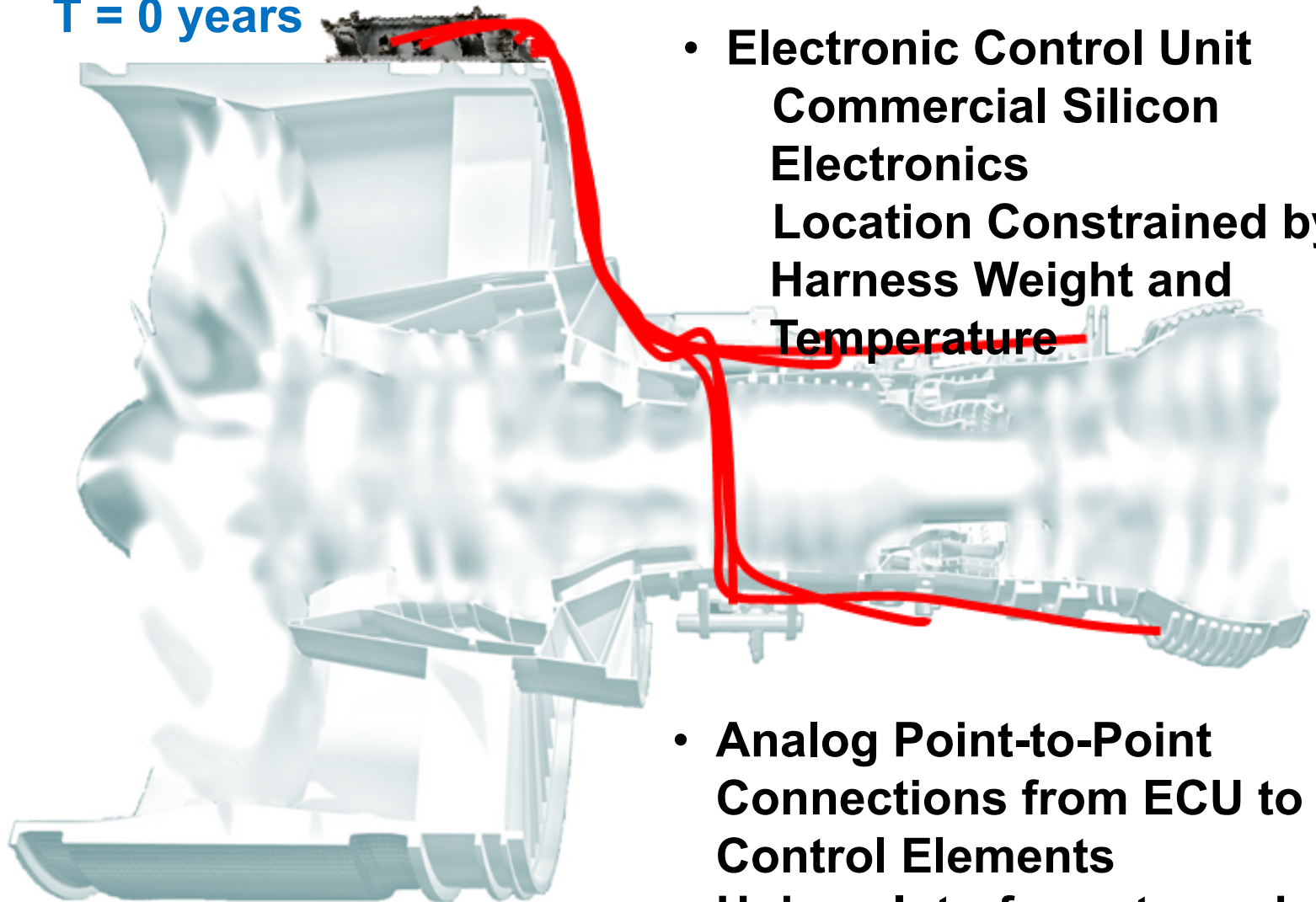


What is the Go Forward Plan?

Transition from Centralized Architecture



T = 0 years



- **Electronic Control Unit
Commercial Silicon
Electronics
Location Constrained by
Harness Weight and
Temperature**

- **Analog Point-to-Point
Connections from ECU to
Control Elements**
- **Unique Interfaces to each
Control Element**

Transition to Core I/O Architecture

... reduced fuel burn



T = 5 years

- **Data Concentrator on Core**
- **Digital Communications to Control Law Processor**

**Control Law Processor
Compact, Commercial Silicon**

- **Legacy Sensors and Actuators**
- **Local Loop Closure**

Transition to Networked Control Architecture

... reduced fuel burn, reduced NOx, reduced noise



T = 10 years

Control Law Processor
Compact, Commercial Silicon

- ***Compact* Data Concentrator**
- **Digital Communications to Control Law Processor**
- **Networked Control Elements**

- **>300 Celsius Electronics**
- **Smart Sensors and Actuators**
- **Embedded Subsystem Control**

Transition to Fully Distributed Architecture

... reduced fuel burn, reduced NOx, reduced noise



T = 15 years

Control Law Processor
Compact, Commercial Silicon

- No Data Concentrator
- Fully Networked control elements and Control Law Processor

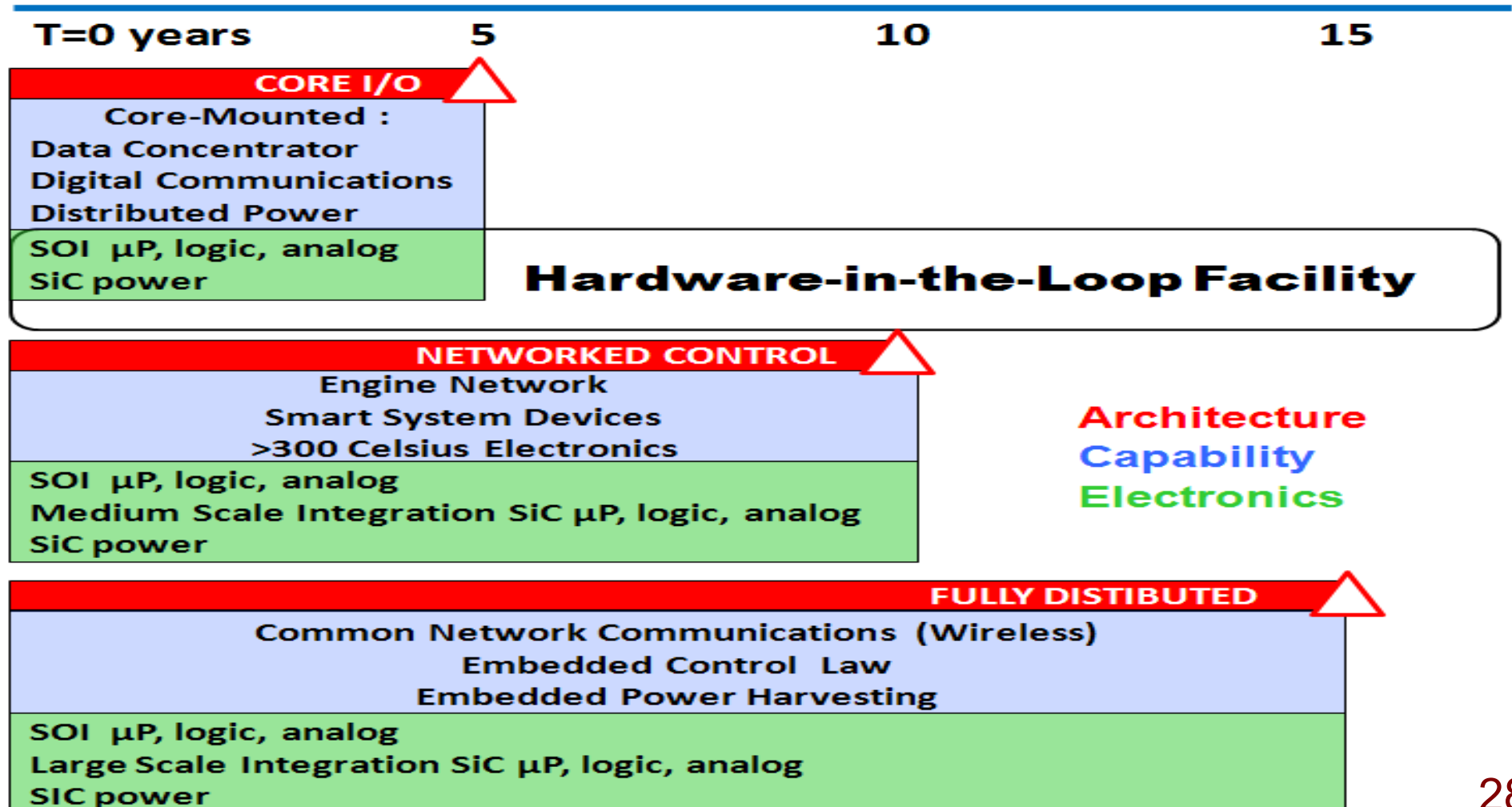
Wireless Capability

- >300 Celsius Electronics
- Fully Embedded Subsystem Control
- Power Scavenging Technologies

Development Plan for Distributed Control



- The DEC barrier is primarily due to the cost of high temperature electronics and the lack of customer pull for their development
- Successful development of DEC will require industry collaboration and a phased implementation to minimize cost and generate technology pull



Hardware-In-The-Loop



A Hardware-In-The-Loop (HIL) test capability is proposed for the near time frame. The vision is to develop a **Common Environment** to solicit broad participation from industry/government/academia for the development of the next generation of control systems.

- The concept of a common environment is based on the *use of open standards* for the interconnection of distributed control element components. The components themselves, and their embedded intellectual property, being unique.
- HIL will enable investigations of distributed control system stability and performance.
- HIL will enhance understanding of distributed controls with regard to system integration, verification, and certification.
- HIL will be complimentary to and provide a means to verify simulation capability
- *A Common Environment HIL will be a focal point for future collaboration*

NASA SBIR/STTR Technologies

Distributed Engine Control Empirical / Analytical Verification Tools

PI: Jonathan DeCastro/ Impact Technologies, LLC. Rochester, NY

Proposal No. A2.07-9372



Identification and Significance of Innovation

Impact Technologies, in collaboration with Prof. R.K. Yedavalli, propose a novel verification environment for eventual rapid certification of distributed engine control systems such as new high-temperature components and control laws. The proposed D-HIL simulator will feature a thermal test chamber capable of subjecting components to harsh engine environments, while functioning as elements in the networked control loop. To verify engine control software, a Global Verification Toolset (GVT) is proposed to assess stability and performance of the assembled distributed engine control system.

Expected TRL at beginning and end of contract (1-9):

Begin: 2; End: 3 to 4

Technical Objectives and Work Plan

Objective: Develop a distributed HIL facility and an associated set of Global Verification Tools useful for certification.

Months 1-2: Configure C-MAPSS real-time engine simulator

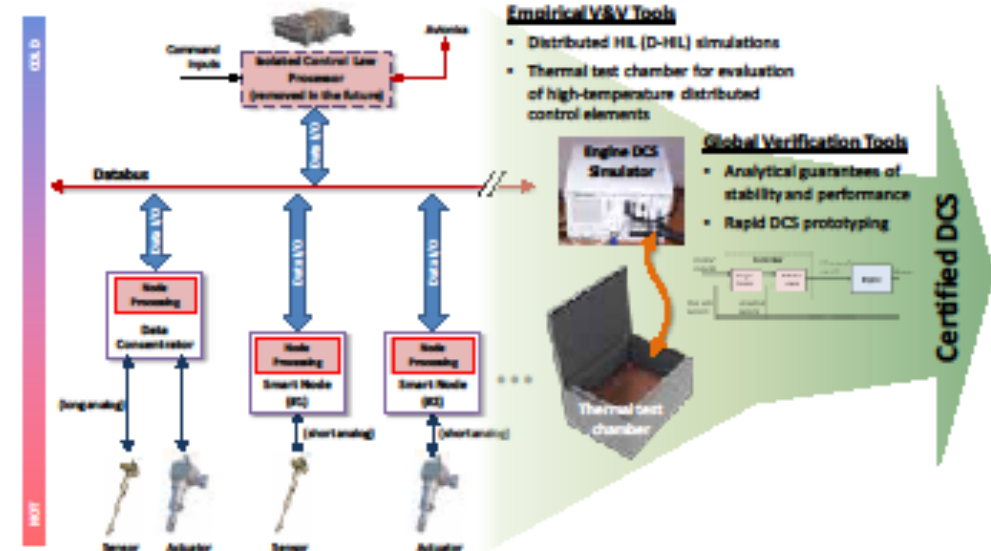
Months 2-5: Develop the Distributed HIL simulation and design and fabricate the thermal test chamber

Months 1-5: Develop the Global Verification Toolset

Months 4-5: Develop user interface for the hardware/software toolsets

Months 5-6: Final demonstration and commercial/government transition planning

At the conclusion of Phase I, the new verification facility and software tools will be demonstrated in a system test using the C-MAPSS engine.



NASA and Non-NASA Applications

The proposed tools will enable the development of distributed aircraft propulsion control systems and flight control avionic systems. The verification toolset will also benefit fly-by-wire systems and the automotive, energy, and manufacturing industries. Impact Technologies will position the hardware simulator for inclusion in future planned NASA/DoD-led Distributed Engine Control demonstrations.

Firm Contacts

Jonathan A. DeCastro, Impact Technologies, LLC
200 Canal View Blvd, Rochester, NY 14623
Tel: (585) 424-1990 Ext: 148; Fax: (585) 424-1177
E-mail: Jonathan.DeCastro@impact-tek.com

NON-PROPRIETARY DATA

NASA SBIR/STTR Technologies A2.07-8712 Data Concentrator for Modular and Distributed Control of Propulsion Systems

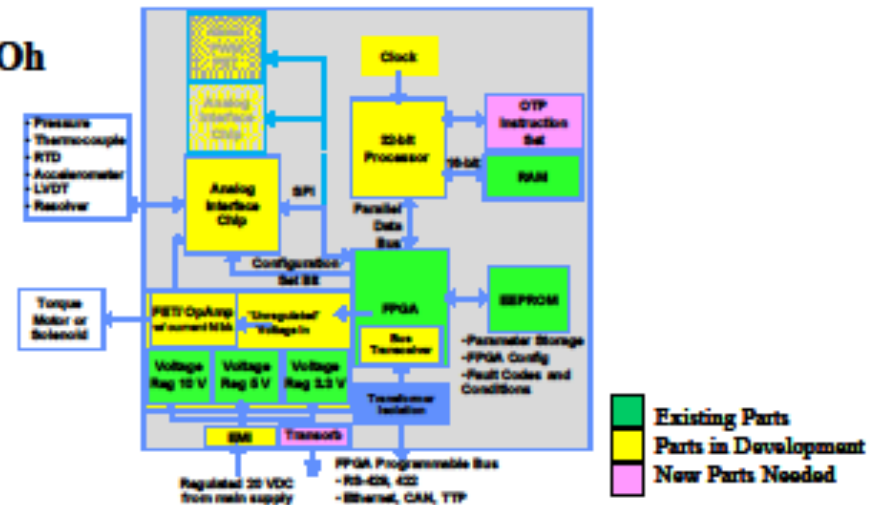


PI: Mike Willett
Orbital Research Inc. -Cleveland Oh

Identification and Significance of Innovation

The Proposed Innovation: *Orbital Research Inc. proposes in this NASA Phase I/Phase II SBIR project to design, develop, and test a High Temperature (HT) Data Concentrator that will, for the first time, enable the implementation of a modular and flexible distributed control architecture for next generation turbine engines. Orbital will accomplish this significant advance by integrating existing and developmental application specific integrated circuits (ASICs) into a functional high-temperature (200-225°C continuous operation) module ready for high temperature testing*

Expected TRL Range at the end of Contract (1-9): Phase I - TRL 3



HT electronics provide high reliability at 200C

Technical Objectives and Work Plan

Technical Objectives

- Develop Detailed Specification for the Data Concentrator
- Define Requirements for the OTP, Transorb, and Protocol Driver
- Prepare Documentation and Chip Designs for Phase II

Work Plan

- Create Specifications for Data Concentrator
- Design HT Transorb
- Design High Temperature OTP
- Analyze Protocol Options

NASA and Non-NASA Applications

Within NASA the variants of the Data Concentrator can be incorporated into:

- Ground testing of rocket engines;
- Ground testing of turbine engines (including VAATE);
- Sensor webs and distributed sensors (non-engine);
- Highly reconfigurable sensors

Defense and Commercial applications include:

- Next generation military and civilian aircraft turbine engines, including rotorcraft, UAS, and land vehicles (very large market potential);
- Down-hole drilling and geothermal drilling controls;
- Prognostic Health Management (PHM)/Integrated System Health Management (ISHM);
- Chemical, nuclear, refinery, and process plant instrumentation
- Powertrain controls for internal combustion engines, gas or diesel (for instance an improved waste gate turbo-booster).

Firm Contacts

Honeywell; Hamilton Sunstrand; Boeing; Pratt & Whitney; General Electric; Rolls Royce; BAE; Parker Hannifin; Woodward; Goodrich

Summary and Conclusions



Without distributed control (constraints) –

- Gas turbine engines are unlikely to achieve the full performance potential of improvements in other technology areas.
- The lifecycle costs and weight of control systems will continue to increase relative to the engine system.

With distributed control (enabler) –

- New control-based technologies can be introduced into the engine system which further improve performance and lower cost.

Distributed Control requires advances in power distribution, network communications, systems integration but especially **high temperature electronics** to be successful.

The implementation roadmap is designed to cooperatively leverage government and industry efforts to achieve an initial implementation success and assumes increasing **customer pull** and continued stakeholder **collaboration** will enable full technology maturation.

Acknowledgements



Support for this work is provided by the NASA Fundamental Aeronautics Program, Subsonic Fixed Wing Project

The Distributed Engine Control Working Group, a consortium of US government and turbine engine industry representatives, has been a major contributor to this effort

DECWG

Distributed Engine Control Working Group